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(71)(72) Applicant and Inventor: IVRI, Yehuda [IL/US]; 38 Silkberry, Irvine, CA 92714 (US).

(74) Agent: GESS, Albin, H.; Price, Gess & Ubell, 2100 S.E. Main Street, Suite 250, Irvine, CA 92714 (US).

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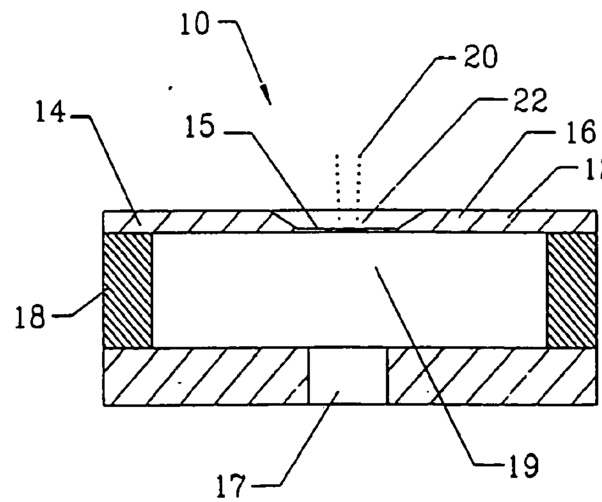

(57) Abstract

A fluid injection device (10) that ejects a quantum of fluid in response to an electrical signal. The device operates without kinematic elements or a pump and it does not need external pressure. In a preferred embodiment a circular membrane (12) is mounted at its perimeter (14) to an oscillating base (18). The membrane is shaped so that its cross-section is reduced towards its center (16). The membrane oscillates at frequency which is at or near its natural frequency. Because of the configuration of the membrane and the frequency of oscillation thereof, the center of the membrane oscillates over an amplitude which is significantly higher than the oscillation amplitude of the perimeter. The center area of the membrane is provided with one or more tapered apertures (22). One opening of each tapered aperture is in fluid communication with a reservoir of fluid (17).

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ULTRASONIC FLUID EJECTOR

BACKGROUND OF THE INVENTION

Cross-Reference to Related Applications

The priority of the following earlier application is hereby claimed. U.S. Patent Application Serial No. 07/726,777, filed on July 8, 1991.

1. Field of the Invention

The present invention relates generally to the filed of fluid injection and more specifically to fuel injection, fluid dispensing, and non-aerosol spray. The invention provides a means for metering flow rate by electronic control of oscillations of a membrane. The fluid injection system is particularly advantageous in vehicle engines for fuel injection, and for liquid dispensing in medical and chemical laboratories.

2. Description of Related Art

A means for injecting fuel into the cylinder of an engine and the proper time in the cycle of operation is a necessary component for operation of a compression ignition engine. Injection of fuel into either the manifold or into the cylinder on the intake stroke can be employed in spark ignition engines. In either type engine the fuel injection system must do the following:

1) Inject the quantity of fuel demanded by the load on the engine and maintain this metered quantity constant from cycle to cycle and from cylinder to cylinder;

2) atomize the fuel to the required degree; and

3) begin and end the injection sharply.

These requirements have been met in the prior art by relatively complex and expensive pumps and metering systems using relatively exotic injection nozzles and the like. As a result, fuel injection remains a costly aspect of engines that is reflected in increased vehicle selling price or reduced profit. There is therefore, a continuing need for a low cost fuel injection device that meets the aforementioned requirements and that is amenable to electronic control to accommodate other technical advances in modern vehicle and engine design.

Precise fuel injection at low cost is also needed in chemical and medical related fields where fractional micro-liter or better precision is needed to control the relative amounts of fluid constituents. Even high resolution syringe pumps can be inadequate for some applications and they can certainly be costly. There is therefore a need in these field as well to provide improved fluid injection control and relatively low cost and preferably using microprocessor-compatible devices that obviate pumps or other exotic kinematic structures.

SUMMARY OF THE INVENTION

The present invention provides an entirely new and innovative fluid injection device that is especially advantageous in applications that require precise metering of ejection of fluid droplets. A particularly important application is the automotive fuel injection system. The

injector generates microscopic droplets of fuel that are readily atomized. The ejection flow rate may be controlled by electronic means such as a microprocessor. The manufacturing cost of this injection device is only a fraction of the cost of a mechanical injector. The present invention may also be advantageous in laboratory and medical applications for fluid dispensing and fluid metering. The principal innovative feature of the present invention is that it is capable of ejecting droplets of fluid and provide a simple means for controlling the ejection rate without kinematic or acoustic elements or a pump and therefore reduces the manufacturing cost and improves the accuracy of the ejection system. The control over the ejection rate may be provided directly by a microprocessor which further increases the accuracy and reduces the cost of the system.

In the present invention, a membrane of a selected shape is mounted at its perimeter to a base. The base in the preferred embodiment is a piezoelectric device. The membrane is shaped so that its cross-section is reduced toward its center. The piezoelectric device is activated by an oscillating electrical signal the frequency of which is preferably equal to or close to the natural frequency of the membrane. In the preferred embodiment herein a second or higher modal frequency is utilized. Because of the selected frequency of oscillation thereof, the center area of the membrane oscillates over a distance which is significantly greater than the oscillation of the base. Thus, for example, in a preferred embodiment of the invention described herein, this oscillation distance or amplitude at the base is one ten-thousandth of an inch. However, because of the shape of the membrane and frequency of oscillation selected, the amplitude of oscillation at the center of the membrane is fifteen to twenty times greater than that at the base. The actual ratio of center oscillation amplitude to base oscillation amplitude is also a function of the structural damping of the membrane. In the preferred

embodiment of the invention described herein, the membrane is highly damped so that the amplitude in its center area is extremely responsive to variations in the base amplitude. The center area of the membrane is provided with one or more apertures which, in the preferred embodiment of the invention described herein, are tapered in cross-section. One opening of each tapered aperture is in fluid communication with a reservoir of fuel or other liquid. The other opening of the aperture is positioned at an appropriate distance from the target which could be a combustion chamber towards which microscopic droplets of fluid from the reservoir are to be propelled. When the amplitude of the center area of the membrane is above a predetermined threshold, the interaction between each tapered aperture and the fluid reservoir, will cause the fluid inside the aperture to compress in the first half of the oscillation cycle and decompress in the second half of the oscillation cycle. The decompression creates cavitation that tears away a droplet of fluid upon each excursion of the membrane. It has been found that by reducing the amplitude of the oscillations below the aforementioned preselected threshold, fluid droplets will not be ejected. Thus, by controlling the amplitude of the oscillations as well as the size and shape of the aperture of the membrane and given variations in fluid parameters such as viscosity and the like, one can readily provide a means for controlled ejection of droplets of fluid with extremely high accuracy and at low cost as compared to prior art fluid injection devices.

It is therefore a principal object of the present invention to provide a fluid injection device capable of ejecting microscopic size fluid droplets without a mechanical pump or external pressure and without kinematic, acoustic or thermal elements.

It is an additional object of the present invention to provide a fluid injection device comprising a mechanical oscillator provided with tapered apertures having one opening in fluid communication with a fluid reservoir and another opening facing a target.

It is an additional object of the present invention to provide control over fluid ejection flow rate by means of electronic circuitry such as a microprocessor.

It is still an additional object of the present invention to provide a fluid injection device comprising a high frequency mechanical oscillator and a membrane having a selected shape for amplification of oscillation amplitude.

It is still an additional object of the present invention to provide a droplet injection device comprising a membrane provided with tapered apertures that oscillate with frequency and amplitude that produce compression and cavitation of a fluid inside the aperture during each cycle of oscillation.

BRIEF DESCRIPTION OF THE DRAWINGS

The aforementioned objects and advantages of the present invention as well as additional objects and advantages thereof will be more fully understood hereinafter as a result of detailed description of a preferred embodiment when taken in conjunction with the following drawings in which:

Fig. 1 is a schematic illustration of the fluid ejecting device of the present invention shown configured for use for fuel injection;

Fig. 2 is a schematic illustration of the present invention shown in its oscillating configuration;

Fig. 3 is a top view of the membrane of the present invention;

Fig. 4 is a bottom view of the membrane of the present invention;

Fig. 5 is an enlarged cross-sectional view of the center area of the membrane illustrating that portion of the membrane shown in Fig. 2 in the circle labeled "see Fig. 5";

Fig. 6 is an enlarged elevational view of the center area of the membrane of the present invention showing a preferred aperture shape;

Figs. 7 and 8 are schematic illustrations of the fluid characteristic within a tapered aperture during each half of an oscillation cycle; and

Figs. 9 and 10 are schematic illustrations of an alterative embodiment which employs a different structure for producing mechanical oscillations.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now first to Fig. 1 it will be seen that the fluid ejection device 10 of the present invention comprises a membrane 12 having a perimeter area 14 and a center area 16. The perimeter 14 of membrane 12 is affixed to an oscillator 18 which may for example be piezo-ceramic. The center area 16 of membrane 12 is provided with a planar surface 15 through which there are apertures 22. The portion of center 15 having the apertures is in contact with a source of fluid 17 which supplies fluid 19 to produce an ejection of fluid droplets 20.

The oscillatory motion of the membrane 12 is shown in Fig. 2. It will be seen therein, that the perimeter 14 of the membrane 12, by virtue of its contact with the oscillator 18, oscillates in a vertical direction as viewed in Fig. 2 with an oscillating characteristic shown in the graph at the right-most portion of Fig. 2. As also seen in Fig. 2, the center 16 of the membrane 12, oscillates at the same frequency as the perimeter 14, but with a much larger amplitude as seen in the graph on the left-most portion of Fig. 2. The graphs of Fig. 2 are for purposes of illustration and are not necessarily drawn to relative scale.

The significantly larger oscillation amplitude of the center of the membrane in Fig. 2, as compared to the perimeter thereof, is due primarily to two factors. One is the shape of the membrane 12 and the other is the frequency of oscillation that is selected for activation of the oscillator 18. More specifically, membrane 12 is configured so that its cross-section is reduced toward the center. The membrane configuration may be understood best by referring to Figs. 2, 3 and 4 which illustrate a preferred embodiment thereof. The apertures 22 in membrane 12 may be understood best by referring to Fig. 5 and 6. As seen therein, the center portion 15 of the membrane 12 is provided with apertures 22, each characterized by a tapered wall 24, forming a large opening 26 on one side thereof. The thickness of the center 15 of the membrane 12 in the preferred embodiment shown herein is 0.003 inches. Each aperture 22 is positioned at or near the center of the membrane and is circular in shape with large opening 26 having a radius of 0.005 inches and the small opening 28 thereof having a radius of 0.0015 inches.

The shape of membrane 12 and, in particular, the reduction in cross-section of the membrane between its perimeter 14 and its center 16, is selected to provide a

significant increase in amplitude of oscillation between the perimeter and the center of membrane 12. This increase in oscillation amplitude has been found to occur at particular frequencies of oscillation of the membrane 12 such as at the second harmonic of the natural oscillating frequency of the membrane. In the preferred embodiment of the present invention, it is desirable to have a damping ratio between the center area and the perimeter of the membrane of at least 10, depending upon the voltage applied to the oscillator 18 and its mechanical responsiveness thereto.

When the center of the membrane oscillates with an amplitude which exceeds a preselected threshold, fluid droplets are ejected from aperture 22 at the frequency of oscillation of oscillator 18. Thus by controlling the amplitude of the perimeter oscillation and thus the amplitude of the center oscillation so that it is either above or below this threshold ejection level, the ejection of fluid droplets may be readily controlled. In one embodiment that has been reduced to practice, the oscillation amplitude is 0.0001 inches at the perimeter. The frequency of oscillation is approximately 60,000 Hz., which corresponds to the second modal frequency of the membrane 12. The fuel droplet ejection level, that is the level above which the amplitude of oscillation of the center 15 of the membrane 12 causes fuel droplets to be ejected therefrom, is approximately 0.0016 inches. The perimeter oscillation is adjusted so that the center oscillation varies in amplitude from cycle to cycle, so that it is just above the ejection level and below the ejection level upon alternate cycles. The actual ejection level threshold, that is the actual oscillation amplitude of the center of the membrane which causes the ejection of fuel droplets, depends upon the characteristics of the fluid selected, as well as the shape and dimensions of the aperture 22. In the particular refereed embodiment shown herein, the ejection level is achieved using gasoline fuel.

As shown in Figs. 7 and 8, the fluid 19 continuously adheres through solid/fluid surface interaction to the large opening 26 of aperture 22. The fluid is compressed in the first half of the oscillation (Fig. 7) when the membrane strokes toward the fluid the decompresses in the second half of the oscillation cycle (Fig. 8). The decompression occurs simultaneously when the membrane strokes away from the fluid reservoir. One droplet is ejected each time the amplitude of oscillation of the aperture element 15 exceeds the ejection level threshold. The number of droplets and spacing therebetween, are a function of the frequency of oscillation. In the preferred embodiment hereof, at a 60,000 Hz. oscillation frequency, it has been found that when the ejection amplitude is continually above the threshold level, droplets are attached to each other and form a continuous stream. By altering the oscillation amplitude such as by reducing it below the threshold level every second cycle, the droplets can be separated. This feature is particularly advantageous in fuel injection systems. It will be understood however, that with selected changes in the shape of the membrane 12, the characteristic of the fluid and in the shape and dimensions of aperture 22, the selected frequency of operation may vary from that recited herein. Nevertheless, based upon the preferred embodiment disclosed herein, it will now be understood that ejection may be achieved by the present invention and that in fact, fluid-droplet ejection at frequencies exceeding 60,000 Hz. is readily achieved thereby.

An alternative embodiment of the invention is illustrated in Figs. 9 and 10. This alternative embodiment is merely one example of the numerous additional implementations that may be employed to produce oscillating action with at least one tapered aperture. As shown in Figs. 9 and 10, this embodiment is similar to an acoustic tone generator, in that it comprises a membrane 30 having a piezoelectric layer 31. The membrane, which is provided

with tapered apertures 28 near its center, encloses a container 32 which comprises a fluid supply line 33. Terminals 35 permit the application of an alternating voltage to the piezoelectric layer 31 which then responds by alternating expansion and contraction membrane 30 bows in and out in response to the alternative voltage thereby producing the fluid-droplet ejection described for the preferred embodiment.

It will now be understood that what has been disclosed herein comprises a novel and highly innovative fluid ejection device readily adapted for use as a fuel injector in internal combustion engines where small droplets of fuel are required as well as precise control over the flow rate of fuel. The invention comprises a membrane having a perimeter and center area, the center area having a thinner cross-section than the perimeter for amplification of the oscillation amplitude. the perimeter is affixed to a mechanical oscillator for imparting oscillatory motion to the perimeter at a selected frequency and of a selected amplitude. A fuel supply or supply of other fluid is in fluid communication with a tapered hole of the membrane thereby supplying fluid to be ejected from the tapered hole upon each oscillation thereof toward a target each time the oscillation amplitude exceeds a predetermined threshold amplitude. In a preferred embodiment of the invention disclosed herein, the selected frequency of operation is at least a second harmonic of the natural frequency of the oscillation of the membrane. the perimeter of the membrane is oscillated by a piezoelectric element or other mechanical oscillator which oscillates in response to an applied electric voltage.

Because of the shape of the membrane and the use of a natural oscillating frequency thereof, the center oscillation amplitude of the membrane is at least 10 times greater than the perimeter oscillation amplitude when the

average structural damping of the membrane is at least 10 percent. A damping ratio of 10 percent or greater is preferred to use in the present invention in order to make the center of the membrane extremely responsive to variations of the oscillating amplitude at the perimeter of the membrane.

Those having skill in the art to which the present invention pertains will now, as a result of the applicant's teaching herein, perceive various modifications and additions which may be made to the invention. By way of example, the shapes, dimensions and materials disclosed herein are merely illustrative of a preferred embodiment which has been reduced to practice. However, it will be understood that such shapes, dimensions and materials are not to be considered limiting of the invention which may be readily provided in other shapes, dimensions and materials.

I claim:

1. An ejection device for use in fluid ejection systems, the device of the type producing fluid droplets on demand and ejecting such droplets toward a target; the device comprising;

a membrane having a perimeter and a center, the center having at least one tapered aperture;

a mechanical oscillator attached to the said membrane for imparting oscillating motion thereto at a selected frequency and of a selected amplitude; and a liquid supply in fluid communication with said center of said membrane for supplying fluid to be ejected by said center upon each oscillation thereof toward said target exceeding a threshold amplitude.

2. The ejection device recited in Claim 1 wherein said selected frequency is a natural oscillating frequency of said membrane.

3. The ejection device recited in Claim 1 wherein said oscillator comprises a piezoelectric material which oscillates in response to an applied oscillating electrical voltage.

4. The ejection device in Claim 1 wherein said membrane is shaped to provide a ratio of center oscillation amplitude to perimeter amplitude which is at least 10 when the average structural damping ratio of said membrane is at least 10 percent and said selected frequency is a harmonic of the natural oscillating frequency of said membrane.

5. The ejection device recited in Claim 1 wherein said selected frequency and amplitude are sufficient to compress the fluid inside said tapered aperture in the first half of a cycle of each oscillation and eject fluid in the second half of a cycle of oscillation.

6. The ejection device recited in Claim 1 wherein fluid droplets are ejected by said center of said membrane only when said center oscillation amplitude exceeds said threshold amplitude.

7. The ejection device recited in Claim 1 wherein each said aperture has a first opening for receiving fluid from said supply and a second opening from which fluid droplets are ejected toward said target.

8. The ejection device recited in Claim 7 wherein said first opening is larger than said second opening.

9. In a fluid injection system, a fluid droplet ejection device comprising:

a mechanical member constrained at a portion thereof and free to move at another portion thereof and adapted for relative amplitude amplification between its constrained portion and its free portion in response to oscillations at its natural frequency;

said mechanical member having a tapered aperture in its free portion;

an oscillator for imparting mechanical oscillations to said mechanical member in response to an electrical signal; and

a source of fluid for supplying fluid to said aperture.

10. The ejection device recited in Claim 9 wherein said tapered aperture comprises an entry opening for receiving fluid and an exit opening for ejecting said droplets.

11. The ejection device recited in Claim 9 further comprising means for ejecting a droplet of fluid upon each oscillation of said free portion which exceeds a preselected amplitude.

12. The ejection device recited in Claim 8 wherein the frequency and amplitude of oscillation at said free portion are sufficient to compress the fluid inside the aperture in the first half of an oscillation cycle and create cavitation of fluid in said aperture in the second half of an oscillation cycle.

13. The ejection device recited in Claim 9 wherein said oscillation amplitude and frequency of the said mechanical member is sufficient to compress the fluid in said tapered aperture when the said mechanical member moves toward said fluid source.

14. The ejection device recited in Claim 9 wherein said fluid source comprises a fuel supply for delivering fuel to said free portion of the said membrane for controlled ejection therefrom.

15. The ejection device recited in Claim 14 wherein said tapered aperture receives said fuel and ejects said fuel as droplets at a rate dependent upon said selected frequency.

16. A method for ejecting fluid droplets in a fluid injection system;

the method comprising the steps of:

a) providing a membrane of selected shape having a perimeter and a center;

b) oscillating the said membrane at substantially its natural oscillating frequency;

c) allowing the center of said membrane to oscillate in response to mechanical oscillation of said perimeter of said membrane;

d) providing said center with at least one fluid-droplet-ejecting aperture; and

e) supplying fluid to said aperture.

17. The method recited in Claim 16 wherein the amplitude and natural oscillating frequency of said membrane are sufficient to compress the fluid in the said aperture.

18. A device for ejecting fluid droplets at a selected frequency;

the device comprising:

a surface having an aperture;

said aperture having first and second openings wherein said first opening is larger than said second opening and is in contact with said fluid; and

means for oscillating said aperture at said selected frequency whereby said fluid droplets are ejected from said second opening.

19. The ejecting device recited in Claim 18 wherein said aperture has a conical cross-section.

20. The ejecting device recited in Claim 18 further comprising means controlling said oscillating means for selectively stopping and staring the ejection of said fluid droplets.

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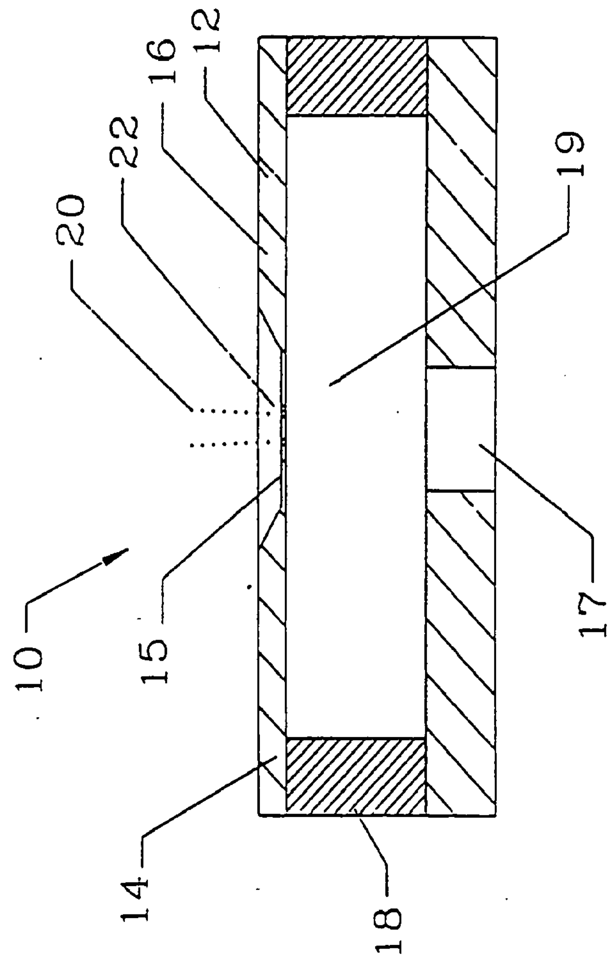

FIG—1

SUBSTITUTE SHEET

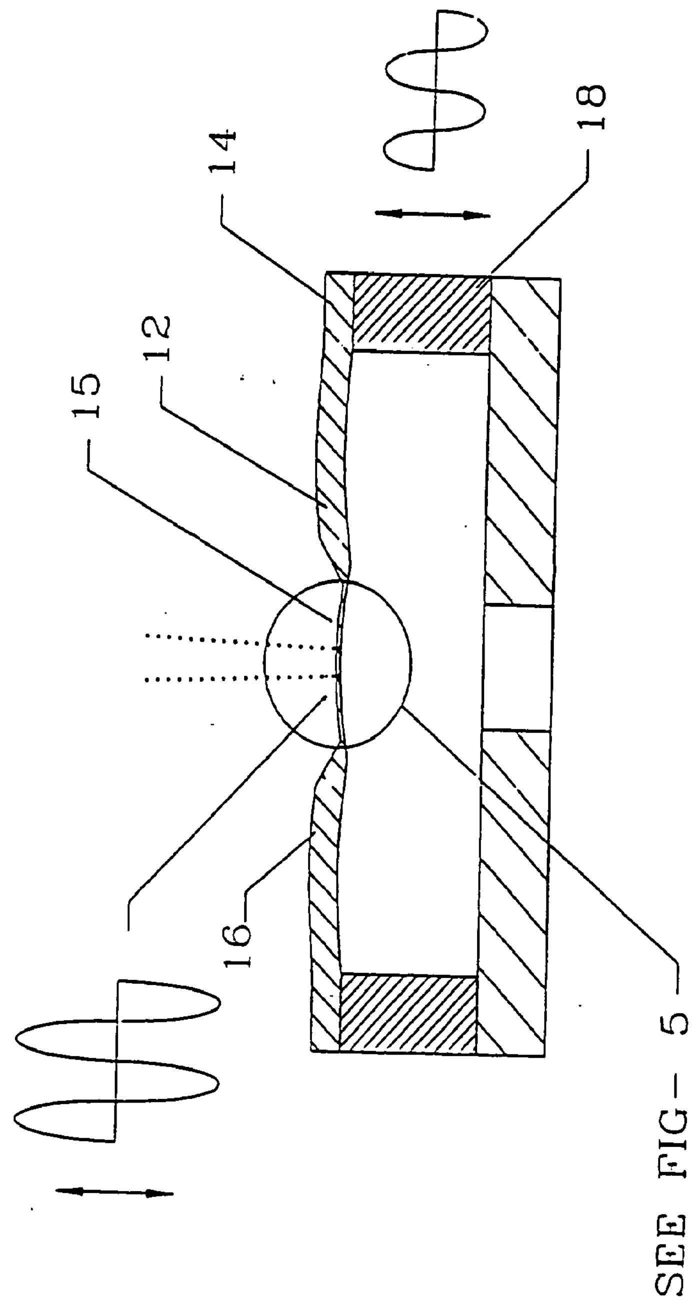

FIG-2

SUBSTITUTE SHEET

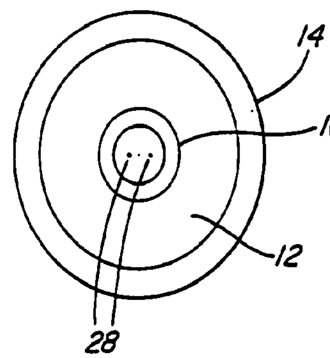

FIG. 3

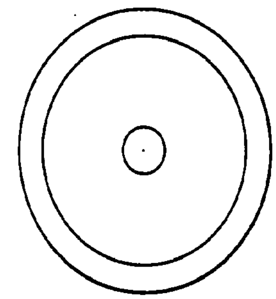

FIG. 4

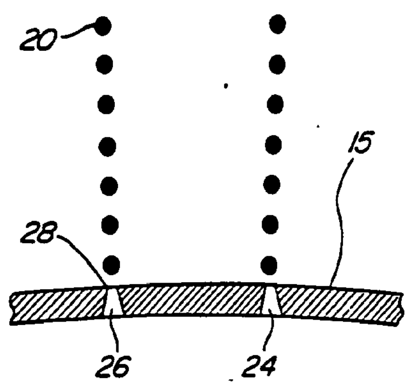

FIG. 5

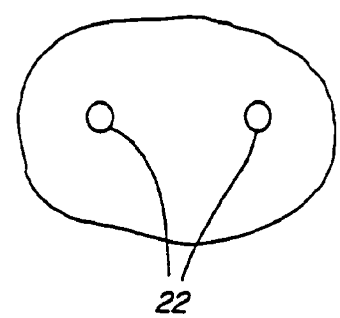

FIG. 6

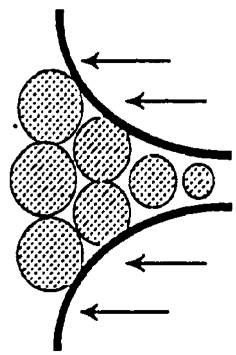

FIG-7

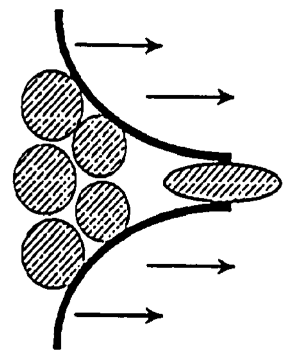

FIG-8

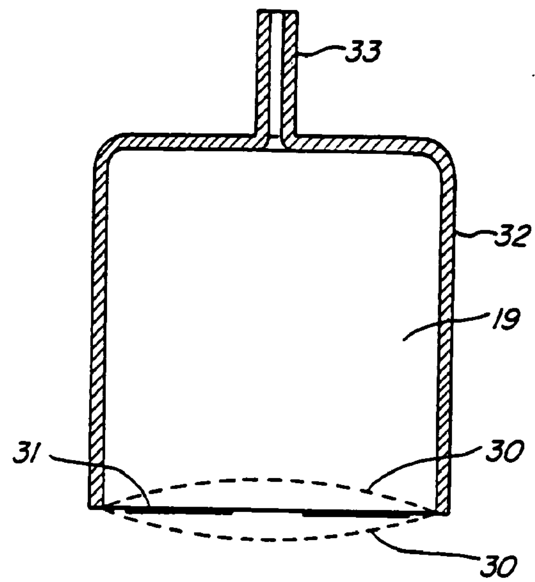

FIG. 9

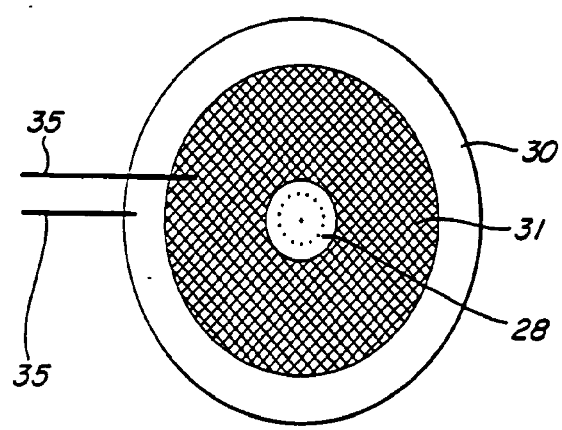

FIG. 10

INTERNATI...AL SEARCH REPORT

PCT/US92/05275

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G01D 15/18
US CL :346/1.1, 140R
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 346/140PD

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US,A,4,539,575 (NILSSON) 03 SEPTEMBER 1985. SEE ENTIRE DOCUMENT	1-20
Y	US,A, 4,544,933 (HEINZL) 01 OCTOBER 1985 SEE ENTIRE DOCUMENT.	1-20
Y	US,A, 4,605,167 (MAEHARA) 12 AUGUST 1986, SEE ENTIRE DOCUMENT	1-20
Y	US,A, 4,620,201 (HEINZL ET AL) 28 OCTOBER 1986. SEE ENTIRE DOCUMENT.	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
28 AUGUST 1992	16 DEC 1992

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